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An Integrated Model for the Danubian Lowland – Methodology and Applications

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Abstract. A unique integrated modelling system has been developed and applied for environmental assessment studies in connection with the Gabcikovo hydropower scheme along the Danube. The modelling system integrates model codes for describing the reservoir (2D flow, eutrophication, sediment transport), the river and river branches (1D flow including effects of hydraulic control structures, water quality, sediment transport), the ground water (3D flow, solute transport, geochemistry), agricultural aspects (crop yield, irrigation, nitrogen leaching) and flood plain conditions (dynamics of inundation pattern, ground water and soil moisture conditions, and water quality). The uniqueness of the established modelling system is the integration between the individual model codes, each of which provides complex descriptions of the various processes. The validation tests have generally been carried out for the individual models, whereas only a few tests on the integrated model were possible. Based on discussion and examples, it is concluded that the results from the integrated model can be assumed less uncertain than outputs from the individual model components. In an example, the impacts of the Gabcikovo scheme on the ecologically unique wetlands created by the river branch system downstream of the new reservoir have been simulated. In this case, the impacts of alternative water management scenarios on ecologically important factors such as flood frequency and duration, depth of flooding, depth to ground water table, capillary rise, flow velocities, sedimentation and water quality in the river system have been explicitly calculated.

Key words: Danube, environmental impacts, floodplain, Gabcikovo, groundwater, hydropower, integrated modelling, river branch.

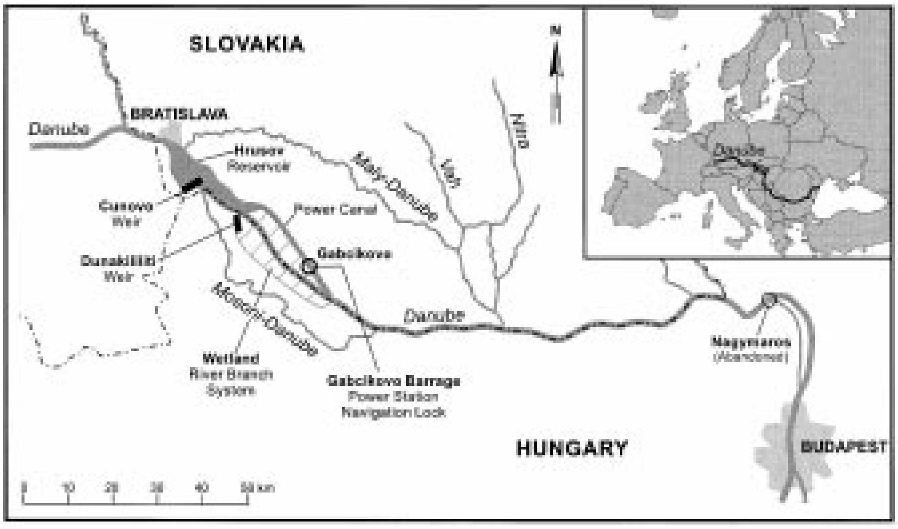


Figure 1. The Danubian Lowland with the new reservoir and the Gabcikovo scheme.

1. Introduction

1.1. THE DANUBIAN LOWLAND AND THE GABCIKOVO HYDROPOWER SCHEME

The Danubian Lowland (Figure 1) in Slovakia and Hungary between Bratislava and Komárno is an inland delta (an alluvial fan) formed in the past by river sediments from the Danube. The entire area forms an alluvial aquifer, which receives around 30 $m^3 s^{-1}$ infiltration water from the Danube throughout the year, in the upper parts of the area and returns it to the Danube and the drainage canals in the downstream part. The aquifer is an important water resource for municipal and agricultural water supply.

Human influence has gradually changed the hydrological regime in the area. Construction of dams upstream of Bratislava together with straightening and embanking of the river for navigational and flood protection purposes as well as exploitation of river sediments have significantly deepened the river bed and lowered the water level in the river and surrounding ground water level. These changes have had a significant influence on the ground water regime as well as the sensitive riverine forests downstream of Bratislava. Despite this basically negative trend the floodplain area with its alluvial forests and associated ecosystems still represents a unique landscape of outstanding ecological importance.

The Gabcikovo hydropower scheme was put into operation in 1992. A large number of hydraulic structures has been established as part of the hydropower scheme. The key structures are a system of weirs across the Danube at Cunovo 15 km downstream of Bratislava, a reservoir created by the damming at Cunovo, a 30 km long lined power and navigation canal, outside the floodplain area, parallel to the Danube River with intake to the hydropower plant, a hydropower plant and two ship-locks at Gabcikovo, and an intake structure at Dobrohost, 10 km downstream of Cunovo, diverting water from the new canal to the river branch system. The entire scheme has significantly affected the hydrological regime and the ecosystem of the region, see, e.g., Mucha *et al*. (1997). The scheme was originally planned as a joint effort between former Czecho-Slovakia and Hungary, and the major parts of the construction were carried out as such on the basis of a 1977 international treaty. However, since 1989 Gabcikovo has been a major matter of controversy between Slovakia and Hungary, who have referred some disputed questions to international expert groups (EC, 1992, 1993a, b) and others to the International Court of Justice in The Hague (ICJ, 1997).

Comprehensive monitoring and assessments of environmental impacts have been made, see Mucha (1995) for an overview. Since 1995 a joint Slovak-Hungarian monitoring program has been carried out (JAR, 1995, 1996, 1997).

1.2. NEED FOR INTEGRATED MODELLING

The hydrological regime in the area is very dynamic with so many crucial links and feedback mechanisms between the various parts of the surface- and subsurface water regimes that integrated modelling is required to thoroughly assess environmental impacts of the hydropower scheme. This is illustrated by the following three examples:

- *Ground water quality*. Based on qualitative arguments it was hypothesised that the damming and creation of the reservoir might lead to changes in the oxidation-reduction state of the ground water. The reason for this is that the reservoir might increase infiltration from the Danube to the aquifer because of increased head gradients. On the other hand, fine sediment matter might accumulate on the reservoir bottom, thereby creating a reactive sediment layer. The river water infiltrating to the aquifer has to pass this layer, which might induce a change in the oxidation status of the infiltrating water. This could affect the quality of the ground water from being oxic or suboxic towards being anoxic, which is undesirable for Bratislava’s water works, most of which are located near the reservoir. Thus, the oxidation-reduction state of the groundwater is intimately linked to a balance between the rates of infiltrating reducing water and the aquifer oxidizing capacity. The infiltrating water is linked to the hydraulic behaviour of the reservoir: how large is the infiltration area and at which rates does the infiltration take place at different locations. However, without an integrated model it is not possible to quantify whether and under which conditions these mechanisms play a significant role in practise, whether they are correct in principle but without practical importance, and what measures should be realised.
- *Agricultural production*. Changes in discharges in the Danube caused by diversion of some of the water through the power canal and creation of a reservoir

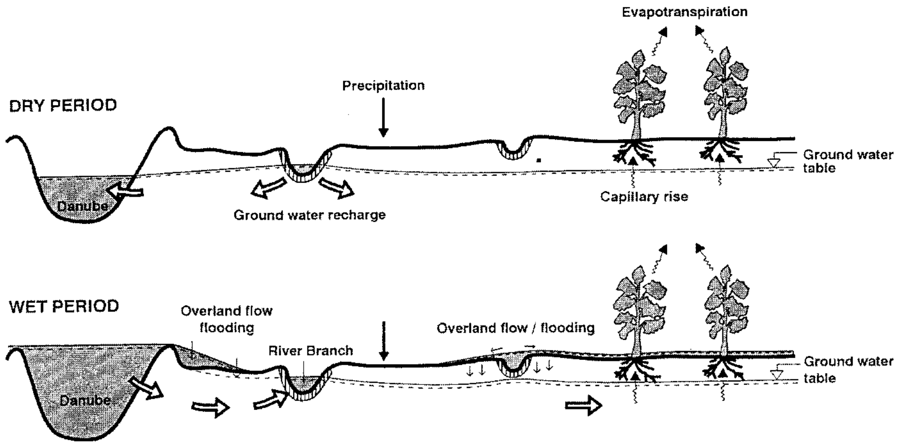


Figure 2. Important processes and their interactions with regard to floodplain hydrology.

would lead to changes in the ground water levels. As the agricultural crops depend on capillary rise from the shallow ground water table and irrigation, the new hydrological situation created by the damming of the Danube might influence both the crop yield, the irrigation requirements and the nitrogen leaching. Traditional crop models describing the root zone are not sufficient in this case, because the lower boundary conditions (ground water levels) are changed in a way that can only be quantified if also the reservoir, the river and canal system and the aquifer are explicitly included in the modelling.

- *Floodplain ecosystem*. The flora and fauna, which in the floodplain area are dominated by the river side branches, depend on many factors such as flooding dynamics, flow velocities, depth of ground water table, soil moisture, water quality and sediments. Also in this case the important factors depend on the interaction between the groundwater and the surface water systems (illustrated in Figure 2), and even on water quality and sediments in the surface water system, so that quantitative impact assessments require an integrated modelling approach.

2. Integrated Modelling System

2.1. INDIVIDUAL MODEL COMPONENTS

An integrated modelling system (Figure 3) has been established by combining the following existing and well proven model codes:

- *MIKE SHE* (Refsgaard and Storm, 1995) which, on a catchment scale, can simulate the major flow and transport processes in the hydrological cycle:

  – 1-D flow and transport in the unsaturated zone

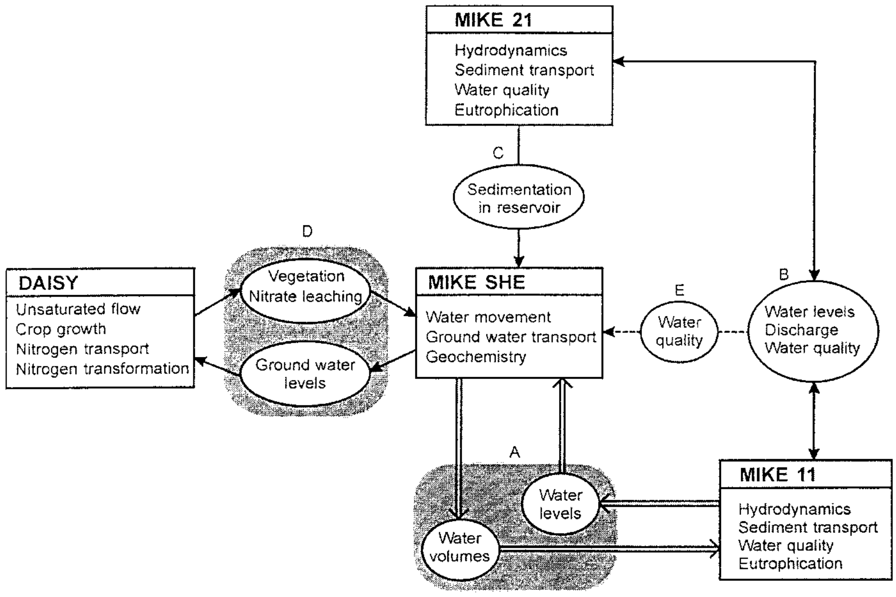


Figure 3. Structure of the integrated modelling system with indication of the interactions between the individual models.

– 3-D flow and transport in the ground water zone
– 2-D flow and transport on the ground surface
– 1-D flow and transport in the river.

All of the above processes are fully coupled allowing for feedback's and interactions between components. In addition, MIKE SHE includes modules for multi-component geochemical and biodegradation reactions in the saturated zone (Engesgaard, 1996).

- *MIKE 11* (Havnø *et al*., 1995), is a one-dimensional river modelling system. MIKE 11 is used for simulating hydraulics, sediment transport and morphology, and water quality. MIKE 11 is based on the complete dynamic wave formulation of the Saint Venant equations. The modules for sediment transport and morphology are able to deal with cohesive and noncohesive sediment transport, as well as the accompanying morphological changes of the river bed. The noncohesive model operates on a number of different grain sizes.
- *MIKE 21* (DHI, 1995), which has the same basic characteristics as MIKE 11, extended to two horizontal dimensions, and is used for reservoir modelling.
- MIKE 11 and MIKE 21 include *River/Reservoir Water Quality (WQ) and Eutrophication (EU)* (Havnø *et al*., 1995; VKI, 1995) modules to describe oxygen, ammonium, nitrate and phosphorus concentrations and oxygen demands as well as eutrophication issues such as bio-mass production and degradation.
- *DAISY* (Hansen *et al*., 1991) is a one-dimensional root zone model for simulation of soil water dynamics, crop growth and nitrogen dynamics for various agricultural management practices and strategies.

2.2. INTEGRATION OF MODEL COMPONENTS

The integrated modelling system is formed by the exchange of data and feedbacks between the individual modelling systems. The structure of the integrated modelling system and the exchange of data between the various modelling systems are illustrated in general in Figure 3 and the steps in the integrated modelling is described further in Section 6.2 and illustrated in Figure 10 for the case of flood plain modelling. The interfaces between the various models indicated in Figure 3 are

A) MIKE SHE forms the core of the integrated modelling system having interfaces to all the individual modelling systems. The coupling of MIKE SHE and MIKE 11 is a fully dynamic coupling where data is exchanged within each computational time step, see Section 2.3 below.
B) Results of eutrophication simulations with MIKE 21 in the reservoir are used to estimate the concentration of various water quality parameters in the water that enters the Danube downstream of the reservoir. This information serves as boundary conditions for water quality simulations for the Danube using MIKE 11.
C) Sediment transport simulations in the reservoir with MIKE 21 provide information on the amount of fine sediment on the bottom of the reservoir. The simulated grain size distribution and sediment layer thickness is used to calculate leakage coefficients, which are used in ground water modelling with MIKE SHE to calculate the exchange of water between the reservoir and the aquifer.
D) The DAISY model simulates vegetation parameters which are used in MIKE SHE to simulate the actual evapotranspiration. Ground water levels simulated with MIKE SHE act as lower boundary conditions for DAISY unsaturated zone simulations. Consequently, this process is iterative and requires several model simulations.
E) Results from water quality simulations with MIKE 11 and MIKE 21 provide estimates of the concentration of various components/parameters in the water that infiltrates to the aquifer from the Danube and the reservoir. This can be used in the ground water quality simulations (geochemistry) with MIKE SHE.

A general discussion on the limitations in the above couplings is given in Section 7 below.

2.3. A COUPLING OF MIKE SHE AND MIKE 11

The focus in MIKE SHE lies on catchment processes with a comparatively less advanced description of river processes. In contrary, MIKE 11 has a more advanced description of river processes and a simpler catchment description than MIKE SHE. Hence, for cases where full emphasis is needed for both river and catchment processes a coupling of the two modelling systems is required.

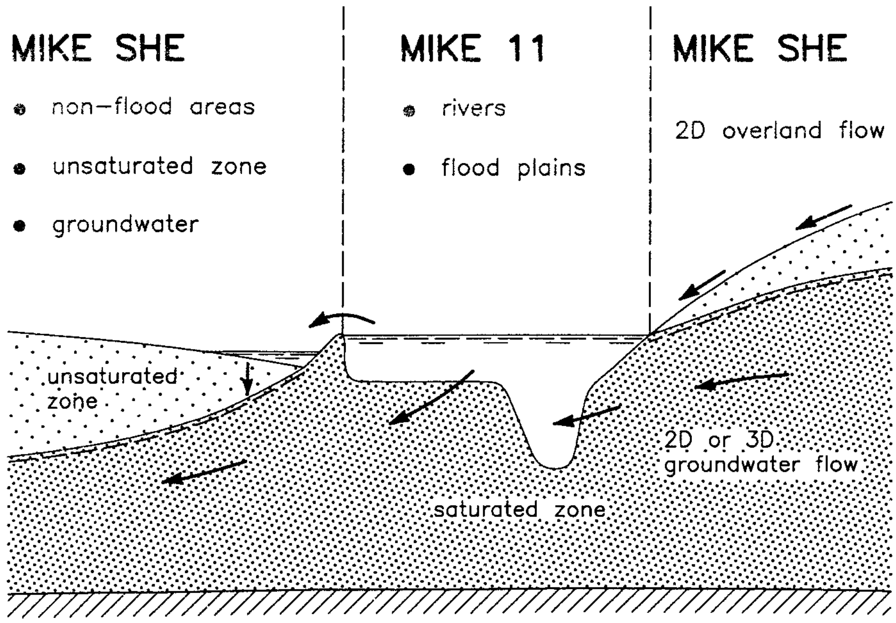


Figure 4. Principles of the coupling between the MIKE SHE catchment code and the MIKE 11 river code.

A full coupling between MIKE SHE and MIKE 11 has been developed (Figure 4). In the combined modelling system, the simulation takes place simultaneously in MIKE 11 and MIKE SHE, and data transfer between the two models takes place through shared memory. MIKE 11 calculates water levels in rivers and floodplains. The calculated water levels are transferred to MIKE SHE, where flood depth and areal extent are mapped by comparing the calculated water levels with surface topographic information stored in MIKE SHE. Subsequently, MIKE SHE calculates water fluxes in the remaining part of the hydrological cycle. Exchange of water between MIKE 11 and MIKE SHE may occur due to evaporation from surface water, infiltration, overland flow or river-aquifer exchange. Finally, water fluxes calculated with MIKE SHE are exchanged with MIKE 11 through source/sink terms in the continuity part of the Saint Venant equations in MIKE 11.

The MIKE SHE–MIKE 11 coupling is crucial for a correct description of the dynamics of the river-aquifer interaction. Firstly, the river width is larger than one MIKE SHE grid, in which case the MIKE SHE river-aquifer description is no longer valid. Secondly, the river/reservoir system comprises a large number of hydraulic structures, the operation of which are accurately modelled in MIKE 11, but cannot be accounted for in MIKE SHE. Thirdly, the very complex river branch system with loops and flood cells needs a very efficient hydrodynamic formulation such as in MIKE 11.

2.4. COMPARISON TO OTHER MODELLING SYSTEMS REPORTED IN LITERATURE

Yan and Smith (1994) described the demand and outlined a concept for a full integrated ground water–surface water modelling system including descriptions of hydraulic structures and agricultural irrigation as a decision support tool for water resources management in South Florida. Typical examples of integrated codes described in the literature are Menetti (1995) and Koncsos *et al*. (1995).

In a review of recent advances in understanding the interaction of groundwater and surface water Winter (1995) mainly describes groundwater codes, such as MODFLOW, which have been expanded with some, but very limited, surface water simulation capabilities. The research activities are characterized as '... although studies of these systems have increased in recent years, this effort is minimal compared to what is needed'. Winter (1995) sees the prospects for the future as follows: 'Future studies of the interaction of groundwater and surface water would benefit from, and indeed should emphasise, interdisciplinary approaches. Physical hydrologists, geochemists, and biologists have a great deal to learn from each other, and contribute to each other, from joint studies of the interface between groundwater and surface water.'

Integrated three-dimensional descriptions of flow, transport and geochemical processes is still rarely seen for groundwater modelling of large basins. Thus, according to a recent review of basin-scale hydrogeological modelling (Person *et al*., 1996) most of the existing reactive transport model codes are based on one-dimensional descriptions.

While many model codes contain a distributed physically-based representation of one of the three main components: ground water, unsaturated zone, and surface water systems, only few codes provide a fully integrated description of all these three main components. For example in an up-to-date book (Singh, 1995) presenting descriptions of 25 hydrological codes only three codes, SHE/SHESED (Bathurst *et al*., 1995), IHDM (Calver and Wood, 1995) and MIKE SHE (Refsgaard and Storm, 1995) provide such integrated descriptions. Among these three codes only MIKE SHE has capabilities for modelling advection-dispersion and water quality. None of the three codes contained options for computations of hydraulic structures in river systems, nor agricultural modelling such as crop yield and nitrogen leaching.

The individual components of the integrated modelling system presented in this paper, we believe, represent state-of-the-art within their respective disciplines. The uniqueness is the full integration.

3. Methodology for Model Construction, Calibration, Validation and Application

The terminology and methodology used in the following is based on the concepts outlined in Refsgaard (1997).

3.1. MODEL CONSTRUCTION

All of the applied models are based on distributed physically-based model codes. This implies that most of the required input data and model parameters can ideally be measured directly in nature.

3.2. MODEL CALIBRATION

The calibration of a physically-based model implies that simulation runs are carried out and model results are compared with measured data. The adopted calibration procedure was based on 'trial and error' implying that the model user in between calibration runs made subjective adjustments of parameter values within physically realistic limits. The most important guidance for the model user in this process was graphical display of model results against measured values. It may be argued that such manual procedure adds a degree of subjectivity to the results. However, given the very complex and integrated modelling focusing on a variety of output results and containing a large number of adjustable parameters, automatic parameter optimisation is not yet possible and 'trial and error' still becomes the only feasible method in practise.

3.3. MODEL VALIDATION

Good model results during a calibration process cannot automatically ensure that the model can perform equally well for other time periods as well, because the calibration process involves some manipulation of parameter values. Therefore, model validations based on independent data sets are required. To the extent possible, limited by data availability, the models have been validated by demonstrating the ability to reproduce measured data for a period outside the calibration period, using a so-called split-sample test (Klemes, 1986). For some of the models, the model was even calibrated on pre-dam conditions and validated on post-dam conditions, where the flow regime at some locations was significantly altered due to the construction of the reservoir and related hydraulic structures and canals.

3.4. MODEL APPLICATION

The validated models have finally been used, as an integrated system, in a scenario approach to assess the environmental impacts of alternative water management options. The uncertainties of the model predictions have been assessed through sensitivity analyses.

4. Selected Results from Model Construction, Calibration and Validation of Individual Components

Comprehensive data collection and processing as well as model calibration and validation were carried out (DHI *et al*., 1995). In the following sections a few selected results are presented for the individual components. Further aspects of model validation focusing on integrated aspects are discussed in Section 5.

4.1. RIVER AND RESERVOIR FLOW MODELLING

The following models have been constructed, calibrated and validated:

- one-dimensional MIKE 11 model for the Danube from Bratislava to Komarno,
- one-dimensional MIKE 11 model for the river branch system at the Slovak floodplain, and
- two-dimensional MIKE 21 model for the reservoir.

The MIKE 11 models have been established in two versions reflecting post- and pre-dam conditions, respectively.

4.1.1. *MIKE 11 River Model for the Danube*

The MIKE 11 model for the Danube is based on river cross-sections measured in 1989 and 1991. The applied boundary conditions were measured daily discharges at Bratislava (upstream) and a discharge rating curve at Komarno (downstream). The model was initially calibrated for two steady state situations reflecting a low flow situation (905 m^3 s^{-1}) and a flow situation close to the long term average (2390 m^3 s^{-1}), respectively. Subsequently, the model was calibrated in a nonsteady state against daily water level and discharge measurements from 1991. The model was finally validated by demonstrating the ability to reproduce measured daily water level data from 1990. Calibration and validation results are presented in Topolska and Klucovska (1995). For the post-dam model some river reaches were updated with cross-sections measured in 1993. In addition, the reservoir and related hydraulic structures and canals were included. As the conditions after damming of the Danube have changed significantly, re-calibration of the post-dam model was carried out for the period April 1993–July 1993. Subsequently, the model was validated against measured data from the period November 1992–March 1993.

4.1.2. *MIKE 11 Model for the River Branch System*

The Danubian floodplain is a forest area of major ecological interest characterised by a complex system of river branches. A layout of the river branch system is shown in Figure 5. The cross-sections in the river branch system were measured during the 1960's and 1970's. The pre-dam model was calibrated against water level and flow data from the 1965 flood. In the post-dam situation, the branch system is fed by an

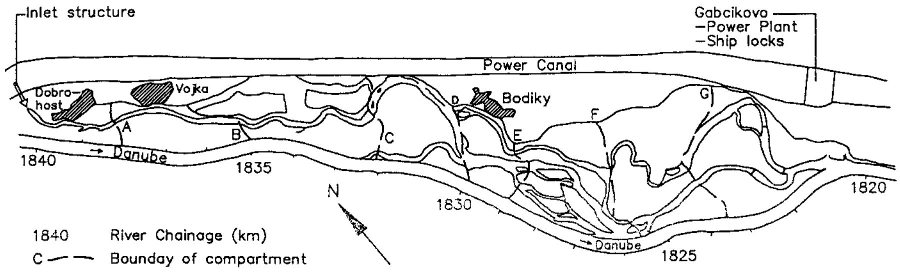


Figure 5. Layout of the river branch system on the Slovakian side of the Danube.

inlet structure with water from the power canal. The system consists of a number of compartments (cascades) separated by small dikes. On each of these dikes combined structures of culverts and spillways are located enabling some control of the water levels and flows in the system. Results of the model calibration against data measured during the summer 1994 are shown in Klucovska and Topolska (1995). Finally, the model was validated by demonstrating the ability to reproduce water levels measured during the summer of 1993. Some of these results are presented in Sørensen *et al*. (1996).

4.1.3. *MIKE 21 Reservoir Model*

A MIKE 21 hydrodynamic model for the reservoir was established based on a reservoir bathymetry measured in 1994. The spatial resolution of the finite difference model is 100×50 m. The model was calibrated against flow velocities measured in the reservoir in the autumn of 1994.

4.2. GROUND WATER FLOW MODELLING

Ground water modelling has been carried out at three different spatial scales:

- A *regional* ground water model for pre-dam conditions (3000 km^2, 500 m horizontal grid, 5 vertical layers).
- A *regional* ground water model for post-dam conditions (3000 km^2, 500 m horizontal grid, 5 vertical layers).
- A *local* ground water model for an area surrounding the reservoir for both pre- and post-dam conditions (200 km^2, 250 m horizontal grid, 7 vertical layers).
- A *local* ground water model for the river branch system for both pre- and post-dam conditions (50 km^2, 100 m horizontal grid, 2 vertical layers).
- A *cross-sectional* (vertical profile) model near Kalinkovo at the left side of the reservoir (2 km long, 10 m horizontal grid, 24 vertical layers).

The regional and local ground water models all use the coupled version of the MIKE SHE and MIKE 11 and hence, include modelling of evapotranspiration and snowmelt processes, river flow, unsaturated flow and ground water flow. The cross-sectional model only includes ground water processes.

4.2.1. *Model Construction*

Comprehensive input data were available and used in the construction of the models. In general, the regional and the local models are based on the same data with the main difference being that the local models provide finer resolutions and less averaging of measured input data. The two regional models, reflecting pre- and post-dam conditions, are basically the same. The only difference is that the post-dam model includes the reservoir and related hydraulic structures and seepage canals.

The models are based on information on location of river systems and cross-sectional river geometry, surface topography, land use and cropping pattern, soil physical properties and hydrogeology. In addition, time series of daily precipitation, potential evapotranspiration and temperature as well as discharge inflow at Bratislava have been used. Comprehensive geological data exist from this area, see e.g., Mucha (1992) and Mucha (1993). The aquifer, ranging in thickness from about 10 m at Bratislava to about 450 m at Gabcikovo, consists of Danube river sediments (sand and gravel) of late Tertiary and mainly Quaternary age. The present model is based on the work of Mucha *et al*. (1992a, b).

4.2.2. *Model Calibration*

The ground water model was calibrated against selected measured time series of ground water levels. The following parameters were subject to calibration: specific yield in the upper aquifer layer, leakage coefficients for the river bed and hydraulic conductivities for the aquifer layers. The soil physical characteristics for the unsaturated zone have been adopted directly from the unsaturated zone/agricultural modelling.

The river model that has been used in the ground water modelling is identical to the MIKE 11 river model of the Danube, which was successfully validated independently as a ‘stand alone model’ (Subsection 4.1, above). When coupling MIKE SHE and MIKE 11 water is exchanged between the two models. The amount of water that recharges the aquifer in the upstream part and re-enters the river further downstream is in the order of 10–60 $m^3\ s^{-1}$ depending on the Danube discharge and on the actual ground water level. The recharge is typically two orders of magnitude less than the Danube discharge, and hence, a re-calibration of the MIKE 11 river model is not required. As the major part of the ground water recharge originates from infiltration through the river bed, the leakage coefficient for the river bed becomes very important. Limited field information was available on this parameter, and hence, it was assumed spatially constant and through calibration assessed to be $5 \times 10^{-5}\ s^{-1}$ for the Danube and Vah rivers and $5 \times 10^{-6}\ s^{-1}$ for the Little Danube. These values are in good agreement with previous modelling experiences (Mucha *et al*., 1992b).

When keeping the specific yield and the leakage coefficients for the river bed fixed the main calibration parameters were the hydraulic conductivities of the saturated zone. About 300 time series of ground water level observations were available for the model area, typically in terms of 30–40 yr of weekly observations. The calibration was carried out on the basis of about 80 of these series for the period 1986–1990. In the parameter adjustments the overall spatial pattern described in the geological model were maintained. Some of the calibration results are illustrated in Figure 6 showing observed Danube discharge data together with simulated and measured ground water levels for three wells located at different distances from the Danube. Wells 694 and 740 are seen to react relatively quickly to fluctuations in river discharge as compared to well 7221, which is located further away from the river. This illustrates how the dynamics of the Danube propagates and is dampened in the aquifer.

4.2.3. *Model Validation*

The calibrated ground water model was validated by demonstrating the ability to reproduce measured ground water tables after damming of the Danube. In this regard the only model modification is the inclusion of the reservoir and related structures and canals. Due to the nonstationarity of the hydrological regime such a validation test, which according to Klemes (1986) is denoted a differential split-sample test, is a demanding test. Figure 7 shows the simulated and observed ground water levels for the same three observation wells as shown for the calibration period in Figure 6. The effects of the damming of the Danube in October 1992, when the new reservoir was established, is clearly seen in terms of increased ground water levels and reduced ground water dynamics when comparing the two figures. These features are well captured by the model.

4.3. GROUND WATER QUALITY

A geochemical field investigation was carried out in a cross-section north of the reservoir near Kalinkovo as a basis for identifying the key geochemical processes and estimating parameter values (see Mucha, 1995). Eleven multi-screen wells were installed close to the water supply wells at Kalinkovo forming a 7.5 km long cross-section parallel to the regional ground water flow direction. The multi-screen wells have been sampled frequently to investigate the ongoing bio-geochemical processes during infiltration of the Danube river water into the aquifer.

A ground water quality model was established for the Kalinkovo cross-sectional profile based on all the measured field data. This model includes a comprehensive description of the bio-geochemical processes such as kinetically controlled denitrification and equilibrium controlled inorganic chemistry based on the well known PHREEQE code. More details are given in Griffioen *et al*. (1995) and

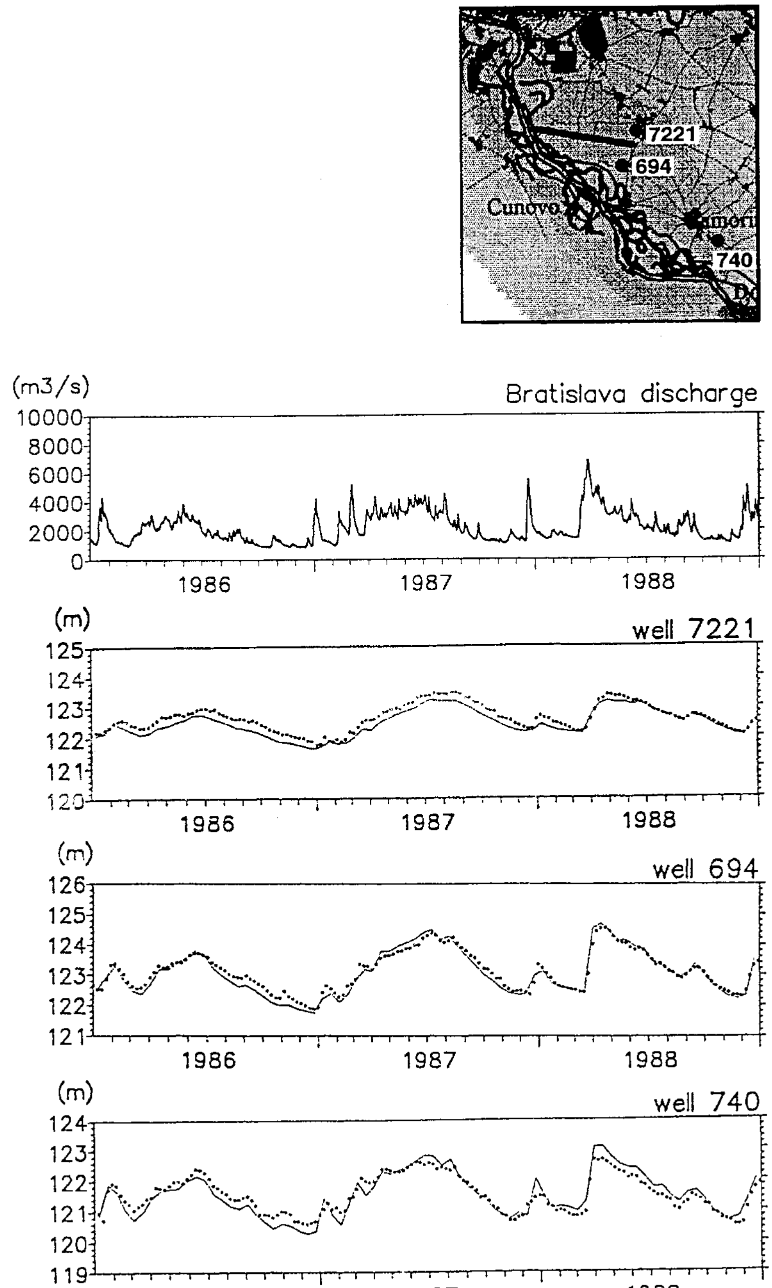


Figure 6. Danube discharge at Bratislava together with simulated and observed ground water levels for three wells before the damming of the Danube (calibration period).

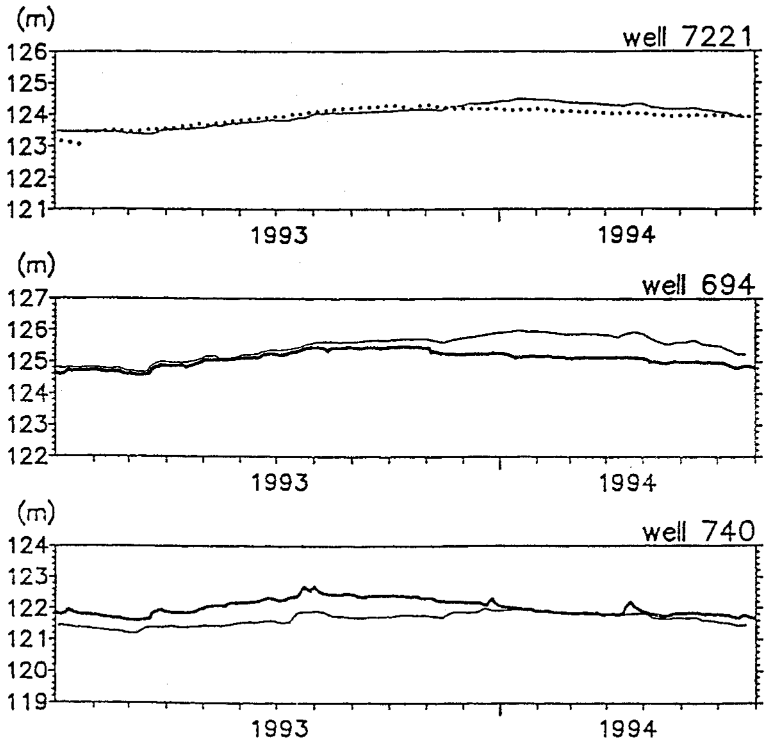


Figure 7. Simulated and observed ground water levels for three wells after damming of the Danube (validation period).

Engesgaard (1996). The transport part of the Kalinkovo cross-section has been calibrated against ^{18}O isotope data. The parameters describing reactive processes have been assessed and adjusted on the basis of the detailed field measurements in the Kalinkovo cross-sectional profile. It was shown that the geochemical model behaves qualitatively correct (Engesgaard, 1996).

4.4. UNSATURATED ZONE AND AGRICULTURAL MODELLING

Modelling of the pre-dam and post-dam conditions of agricultural potential and nitrate leaching risk was carried out using a representative selection of soil units, cropping pattern and meteorological data covering the area between Danube and Maly Danube (Figure 1). The DAISY model uses time-varying ground water levels (simulated with the regional MIKE SHE ground water model) as lower boundary condition, for the unsaturated flow simulations. Cropping pattern and fertiliser application is included in the model based on measurements and statistical data.

The model was calibrated on the basis of data from field experiments carried out during the years 1981–1987 at the experimental station in Most near Bratislava. During this process the crop parameters used in the model were adjusted to Slovak conditions. After the initial model construction and calibration, the model performance was evaluated through preliminary simulations using data from a number of plots located on an experimental field site at Lehnice in the middle of the project area. On the basis of comparisons between measured and simulated values of nitrogen uptake, dry matter yield and nitrate concentrations in soil moisture, the model performance under Slovak conditions was considered satisfactory (DHI *et al*., 1995).

4.5. RIVER AND RESERVOIR SEDIMENT TRANSPORT MODELLING

4.5.1. *Danube River Sediment Transport*

A one-dimensional morphological model was established for the Danube. The model operates with cross-sectional averaged parameters representing the river reach between every computational point (i.e. approximately 500 m), a special technique for comparing 'real' and simulated state variables was required. Therefore, the changes in mean water level over a decade rather than changes in bed elevations were compared between observations and simulations. For this purpose the changes in the so-called 'Low Regulation and Navigable Water Level' (LR-NWL) were used. LR-NWL is specified by the Danube Commission as the water level corresponding to $Q_{94\%}$ which is approximately 980 $m^3\ s^{-1}$. By using such an approach, perturbations in bed levels from one cross-section to another did not destroy the picture of the overall trends in aggradation and degradation of the river bed. The results of the calibration (1974–84) and validation runs (1984–90) are described in Topolska and Klucovska (1995).

4.5.2. *Sediment Transport in the River Branch System*

A one-dimensional fine sediment model was constructed for the river branch system in order to have a tool for quantitative evaluation of the possible sedimentation in the river branch system for alternative water management options. The upstream boundary condition for the model was provided in terms of concentration of suspended sediments simulated by the reservoir model. As virtually no field data on sedimentation in the river branch system were available neither calibration nor validation was possible. Instead, experienced values of model parameters from other similar studies as reported in the literature were used.

4.5.3. *Reservoir Sediment Model*

A two-dimensional fine graded sediment model was constructed for the reservoir. The suspended sediment input was imposed as a boundary condition in Bratislava with time series of sediment concentrations of six suspended sediment fractions with their own grain sizes and fall velocities. The fall velocity for each of the six fractions was assessed according to field measurements. No further model calibration was carried out. The only field data available for validation were a few bed sediment samples from summer 1994 with data on sedimentation thickness and grain size analyses (Holobrada *et al.*, 1994). A comparison of model results and field data indicated that a reservoir sedimentation of the right order of magnitude was simulated. The simulated reservoir sedimentation corresponded to 42% of the total suspended load at Bratislava.

4.6. SURFACE WATER QUALITY MODELLING

4.6.1. *Danube River Model*

A BOD-DO model (MIKE 11 WQ) has been used to describe the water quality in the main stream of the Danube between Bratislava and Komarno. This model describes oxygen concentration (DO) as a function of the decay of organic matter (BOD), transformation of nitrogen components, re-aeration, oxygen consumption by the bottom and oxygen production and respiration by living organisms. As the conditions from pre-dam to post-dam have changed significantly, separate calibrations and validations were carried out. The pre-dam model was calibrated against data from October 1991 and validated against data from April and August/September 1991. The post-dam model was calibrated against data from May 1993 and validated against data from June 1993.

4.6.2. *Model for the River Branch System*

The water quality in the river branches was simulated with a eutrophication model (MIKE 11 EU), in which the algae production is the driving force. The algae growth in this model is described as a function of incoming light, transparency of the water, temperature, sedimentation and growth rate of the algae and of the available inorganic nutrients. The calibration was carried out on the basis of few data available during the period June–August 1993. Due to lack of further data no independent model validation was possible and hence, the uncertainties related to applying the model for making quantitative predictions of the effects of alternative water management schemes may be considerable.

4.6.3. *Reservoir Model*

In the reservoir the driving force is also the algae growth and hence, a eutrophication model (MIKE 21 EU) was applied. The reservoir model was calibrated against measured data from August 1994. This field programme was substantial and resulted in much more data than available for the river branch system. Good correspondence between simulated and observed values were achieved during the calibration period. However, no further data have been available for independent validation tests.

5. Validation of Integrated Model

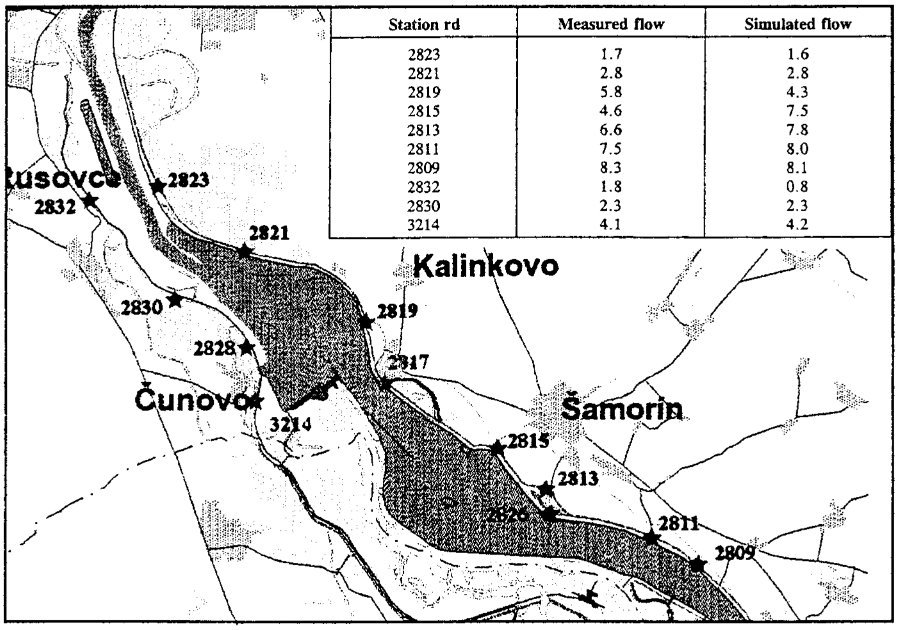
The model calibration and validation have basically been carried out for the individual models using separate domain data for river system, aquifer system, etc. Rigorous validation tests of the integrated model were generally not possible due to lack of specific and simultaneous data on the processes describing the various couplings. Furthermore, although reasonable good assessments of uncertainties of the individual model predictions could be made, it was not obvious how such uncertainty would propagate in the integrated model.

It can be argued that uncertainties in output from one model would in principle influence the uncertainties in other components of the integrated modelling system, thus adding to the total uncertainty of the integrated model. Following this line of argument would lead to the conclusion that the uncertainty of predictions by the integrated model would be larger than the corresponding uncertainty of predictions made by traditional individual models. On the other hand it can also be argued that in the integrated modelling approach the uncertainties in the crucial boundary conditions are reduced, because assumptions needed for executing individual models are substituted by model simulations based on data from neighbouring domains, which, if properly calibrated and validated, better represent the boundary effects. This would lead to the conclusion that the uncertainties in predictions by the integrated model would be smaller than those of the individual models.

In the present study, no theoretical analyses have been made of this problem. Instead, a few validation tests have been made for cases where the couplings could indirectly be checked by testing the performance of the integrated model against independent data. In the following, results from one of these validation tests for the integrated model are shown.

The river-aquifer interaction changed significantly, when the reservoir was established. An important model parameter describing this interaction is the leakage coefficient, which was calibrated on the basis of ground water level data for the predam situation (Subsection 4.2). For the post-dam situation the MIKE 21 reservoir model calculates the thickness and grain sizes of the sedimentation at all points in the reservoir. By use of the Carman-Kozeny formula, the leakage factors are recalculated for the area which was now covered by the reservoir. The model results were then checked against ground water level observations from wells near the reservoir, and it was found, that a calibration factor of 10 had to be applied to the Carman-Kozeny formula. This can theoretically be justified by the fact that the sediments are stratified or layered due to variations in flow velocities during the sedimentation process. The same formula and the same calibration factor was also used for converting all texture data from aquifer sediment samples to hydraulic conductivity values in the model.

Now, how can the validity of the integrated model be tested ? The ground water level observations from a few wells have been used to assess the leakage calibration factor, so although the model output was subsequently checked against data from



Station rd	Measured flow	Simulated flow
2823	1.7	1.6
2821	2.8	2.8
2819	5.8	4.3
2815	4.6	7.5
2813	6.6	7.8
2811	7.5	8.0
2809	8.3	8.1
2832	1.8	0.8
2830	2.3	2.3
3214	4.1	4.2

Figure 8. Measured and simulated discharges in seepage canals. The data are from a particular day in May 1995 and in $m^3\ s^{-1}$.

many more wells, it may be argued that this in itself is not sufficient for a true model validation. Consider instead a comparison of simulated and measured discharges in the so-called seepage canals, which are small canals constructed a few hundred meters away from the reservoir with the aim of intercepting part of the infiltration through the bottom of the reservoir. In Figure 8 it can be seen that the model simulations match the measured data remarkably well at different locations along the seepage canals. Thus, at the two stations most downstream on both seepage canals (stations 2809 and 3214) the agreements between model predictions and field data are within 5%. This is a powerful test, because the discharge data have not been used at all in the calibration process, and because it integrates the effects of reservoir sedimentation, calculation of leakage factors and geological parameters.

6. Model Application – Case Study of River Branch System

6.1. HYDROLOGY OF RIVER BRANCH SYSTEM

The hydrology of the river branch system is highly complex with many processes influencing the water characteristics of importance for flora and fauna (Figure 2). These processes are highly interrelated and dynamic with large variations in time and space. The complexity of the floodplain, with its river branch system, is indicated in Figures 5 and 9 for the 20 km reach downstream the reservoir on the Slovakian side, where alluvial forest occurs. Before the damming of the Danube

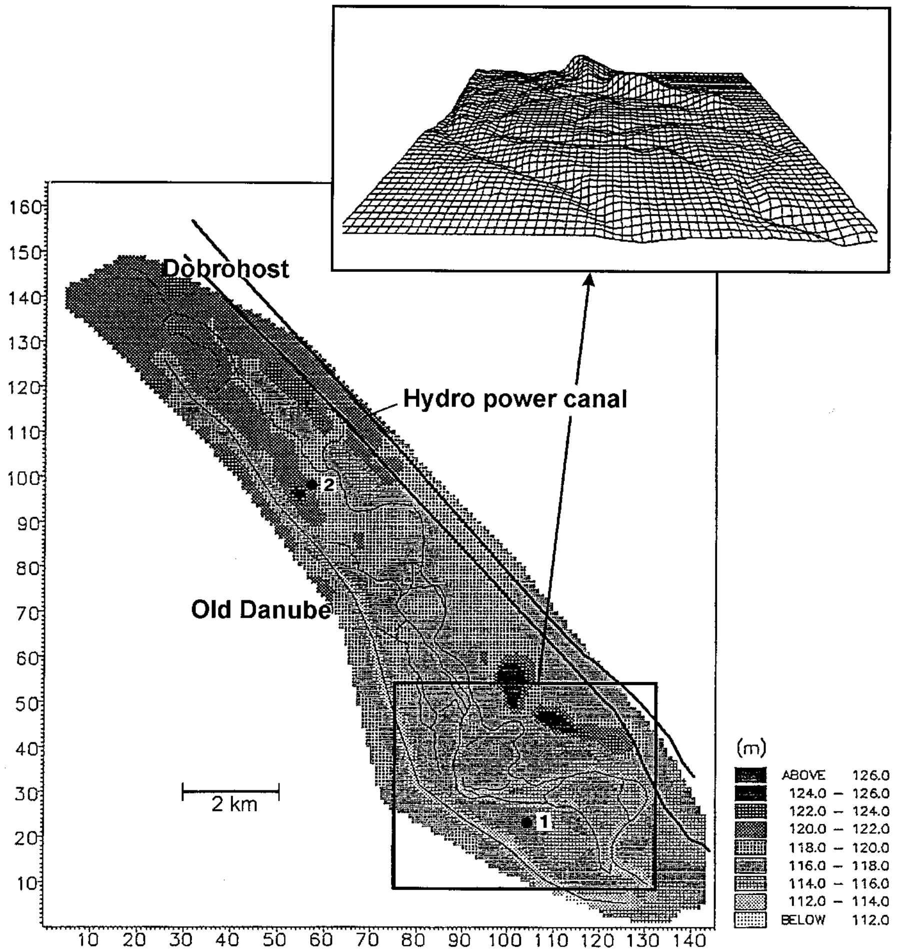


Figure 9. Plan and perspective view of the surface topography, of the river branches and the related flood plains as represented in a model network of 100 m grid squares.

in 1992 the river branches were connected with the Danube during periods with discharge above average. However, some of the branches were only active during flood situations a few days per year. It was anticipated that after the damming, the water level in the Danube would decrease significantly. Therefore, in order to avoid that water drains from the river branches to the Danube, resulting in totally dry river branches, the water outflow from branches into the Danube have been blocked except for the downstream one at chainage 1820 rkm (Figure 5). Now, the river branch system receives water from an inlet structure in the hydropower canal at Dobrohost (Figure 5). This weir has a design capacity of 234 m^3 s^{-1}. Together with the various hydraulic structures in the river branches, it controls the hydraulic, hydrological and ecological regime in the river branches and on the flood plains.

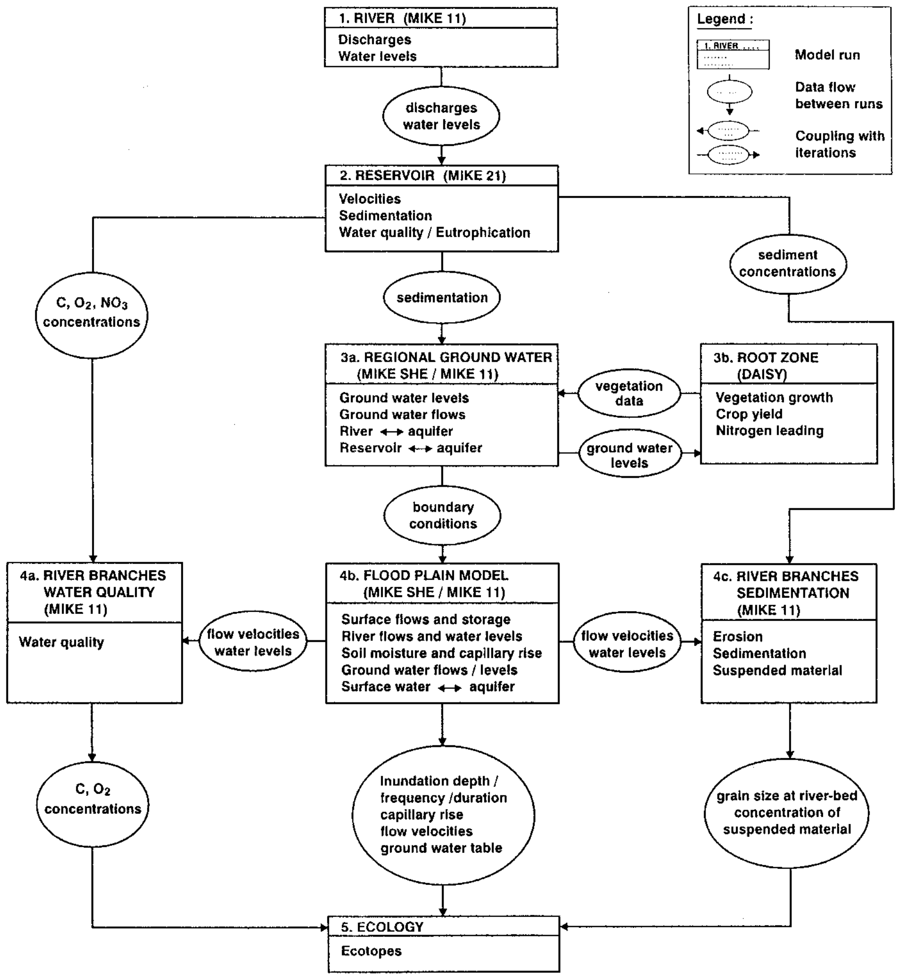


Figure 10. Steps in integrated model for floodplain hydrology.

6.2. MODELLING APPROACH

Comprehensive field studies and modelling analyses are often carried out in connection with assessing environmental impacts of hydropower schemes. Recent examples from the Danube include the studies of the Austrian schemes Altenwörth (Nachtnebel, 1989) and Freudenau (Perspektiven, 1989). However, like in the Austrian cases, the modelling studies have most often been limited to independent modelling of river systems, groundwater systems or other subsystems, without providing an integrated approach as the one presented in this paper.

The models in this study were applied in a scenario approach simulating the hydrological conditions resulting from alternative possible operations of the entire system of hydraulic structures (alternative water management regimes). Thus, one historical (pre-dam) regime and three hypothetical (post-dam) water regimes corresponding to alternative operation schemes for the structures of the Gabcikovo system were simulated (DHI *et al*., 1995). Due to the integration of the overall modelling system each scenario simulation involves a sequence, some times in an iterative mode, of model calculations. For the case of river branch modelling a hierarchical scheme of simulation runs (Figure 10) included the following major steps:

Step 1. Hydraulic river modelling (MIKE 11)

Model simulation: The MIKE 11 model simulates the river flows and water levels in the entire river system and river branches.

Coupling: The model outputs, in terms of flows into the reservoir at the upstream end and downstream outflows through the reservoir structures are used as boundary conditions for the reservoir modelling (Step 2). Furthermore, the flow velocities and water levels are used in the river water quality simulations (Step 4a).

Step 2. Reservoir modelling (MIKE 21)

Model simulation: The MIKE 21 reservoir model simulates velocities, sedimentation and eutrophication/water quality in the reservoir.

Coupling: The flow boundary conditions are generated by the river model (Step 1). Results on sedimentation are used to calculate leakage coefficients. Results on oxygen, nitrogen and carbon can be used as boundary conditions of river water quality, water quality of infiltrating water (Step 3a).

Step 3a. Regional ground water flow (MIKE SHE/MIKE 11)

Model simulation: The coupled MIKE SHE/MIKE 11 model simulates the ground water flow and levels including the interaction with the river system and the reservoir.

Coupling: In the reservoir, the infiltration is simulated on the basis of leakage coefficients, which have been calculated from the amount and composition (grain sizes) of the sedimentation on the reservoir bottom (Step 2). This link between reservoir sedimentation and ground water was shown to be crucial for the model results. Furthermore, an iterative link to the DAISY agricultural model exists (Step 3b). Hence, spatially and temporally varying ground water levels from MIKE SHE/MIKE 11 are used as lower boundary conditions in DAISY, which in turn simulates the leaf area index and the root zone depth which are used as input time series data in MIKE SHE/MIKE 11. The model outputs, in terms of ground water flow velocities, are used as input to the ground water quality simulation. The model results, in terms of river flow velocities and water levels, ground water flow velocities and water levels, are used as time varying boundary conditions for the local flood plain model (Step 4b).

Step 3b. Root zone (DAISY)

Model simulation: The DAISY model simulates the unsaturated zone flows, the vegetation development, including crop yield.

Coupling: The DAISY has an iterative link to the MIKE SHE/MIKE 11 model (as described above under Step 3a).

Step 4a. River branches water quality (MIKE 11)

Model simulation: The MIKE 11 model simulates the river water quality (BOD, DO, COD, NO_3, etc).

Coupling: The model uses data from Step 2 and Step 4b and produces output on concentrations of COD and DO, which are used as input to the ecological assessments (Step 5).

Step 4b. Flood plain model (MIKE SHE/MIKE 11)

Model simulation: The coupled MIKE SHE/MIKE 11 model simulates all the flow processes in the flood plain area including water flows and storages on the ground surface, river flows and water levels, ground water flows and water levels, evapotranspiration, soil moisture content in the unsaturated zone and capillary rise.

Coupling: The model uses data from Step 3a as boundary conditions and provides river flow velocities as the basis for the water quality and sediment simulations (Steps 4a and c). The model provides data on flood frequency and duration, depth of flooding, depth to ground water table, moisture content in the unsaturated zone and flow velocities in river branches, which are key figures in the subsequent ecological assessments (Step 5).

Step 4c. River branches sedimentation (MIKE 11)

Model simulation: The MIKE 11 model simulates the transport of fine sediments through the river branch system. As a result the sedimentation/erosion and the suspended sediment concentrations are simulated.

Coupling: The model uses sediment concentrations simulated by the reservoir model (Step 2) as input. Furthermore, the flow velocities simulated by the local flood plain model (Step 4b) are used as the basis for the sediment calculations. The results, in terms of grain size of the river bed and concentrations of suspended material, are used as input to the ecological assessments (Step 5).

Step 5. Ecology

A correlation matrix between the physical/chemical parameters provided by the model simulations (Steps 4a, b and c) and the aquatic and terrestric ecotopes has been established for the project area. Alternative water management regimes can be described in terms of specific operation of certain hydraulic structures and corresponding distribution of water discharges primarily between the Danube, the Gabcikovo hydropower scheme and the river branch system. The hydrological effects of such alternative operations can be simulated by the integrated model and subsequently, the ecological impacts can be assessed in terms of likely changes of ecotopes.

6.3. THE FLOODPLAIN MODEL

The extent of the floodplain model area is indicated in Figure 5 and a perspective view of the area with the river branch system and floodplains is shown in Figure 9. The horizontal discretization of the finite difference model is 100 m, and the ground water zone is represented by two layers. Several hundreds of cross-sections and more than 50 hydraulic structures in the river branch system were included in the MIKE 11 model for the river system.

For the pre-dam model, the surface water boundary conditions comprise a discharge time series at Bratislava and a discharge rating curve at the downstream end (Komarno). For the post-dam model, the Bratislava discharge time series has been divided into three discharge boundary conditions, namely at Dobrohost (intake from hydropower canal to river branch system), at the inlet to the hydropower canal and at the inlet to Danube from the reservoir. For the groundwater system, time varying ground water levels simulated with the regional ground water models act as boundary conditions. The Danube river forms an important natural boundary for the area. The Danube is included in the model, located on the model boundary, and symmetric ground water flow is assumed below the river. Hence, a zero-flux boundary condition is used for ground water flow below the river.

To illustrate the complex hydrology and in particular the interaction between the surface and subsurface processes model results from a model simulation for a period in June–July 1993 are shown in Figures 11 and 12.

Figure 11 presents the inlet discharges at the upstream point of the river branch system (Dobrohost), while the discharges and water levels at the confluence between the Danube and the hydropower outlet canal downstream of Gabcikovo during the same period are shown in Figure 12. Figure 11 further shows the soil moisture conditions for the upper two m below terrain and the water depth on the surface at location 2. Similar information is shown for location 1 in Figure 12. A soil water content above 0.40 (40 vol.%) corresponds to saturation. Location 2 is situated in the upstream part of the river branch system, while location 1 is located in the downstream part (see Figure 9).

At location 2 (Figure 11) flooding is seen to occur as a result of river spilling (surface inundation occurs *before* the ground water table rises to the surface) whenever the inlet discharge exceeds approximately 60 m^3 s^{-1}. The soil moisture content is seen to react relatively fast to the flooding and the soil column becomes saturated. In contrary, full saturation and inundation does not occur in connection with the flood in the Danube in July, but the event is recognised through increasing ground water levels following the temporal pattern of the Danube flood.

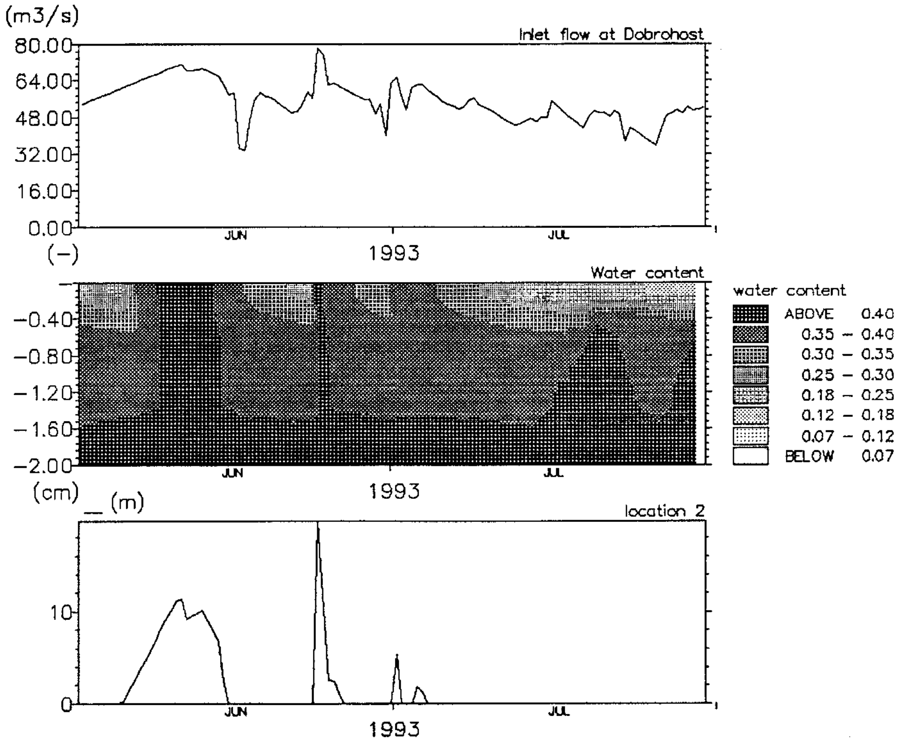


Figure 11. Observed inlet discharge to the river branch system at Dobrohost; simulated moisture contents at the upper two m of the soil profile at location 2 and simulated depths of inundation at location 2 during June–July 1993.

At location 1 (Figure 12) the conditions are somewhat different. During the simulation period location 1 never becomes inundated due to high inlet flows at Dobrohost. However, during the July flood in Danube, inundation at location 1 occurs as a result of increased ground water table caused by higher water levels in river branches due to backwater effects from the Danube. The surface elevation at location 1 is 116.4 m which is 0.4 m below the flood water level shown in Figure 12 at the confluence (5 km downstream of location 1). It is noticed that the inundation at this location occurs as a result of ground water table rise and not due to spilling of the river (surface inundation occurs *after* the ground water table has reached ground surface).

6.4. EXAMPLE OF MODEL RESULTS

As an example of the results which can be obtained by the floodplain model, Figure 13 shows a characterisation of the area according to flooding and depths to groundwater. The map has been processed on the basis of simulations for 1988 for pre-dam conditions. The classes with different ground water depths and flooding

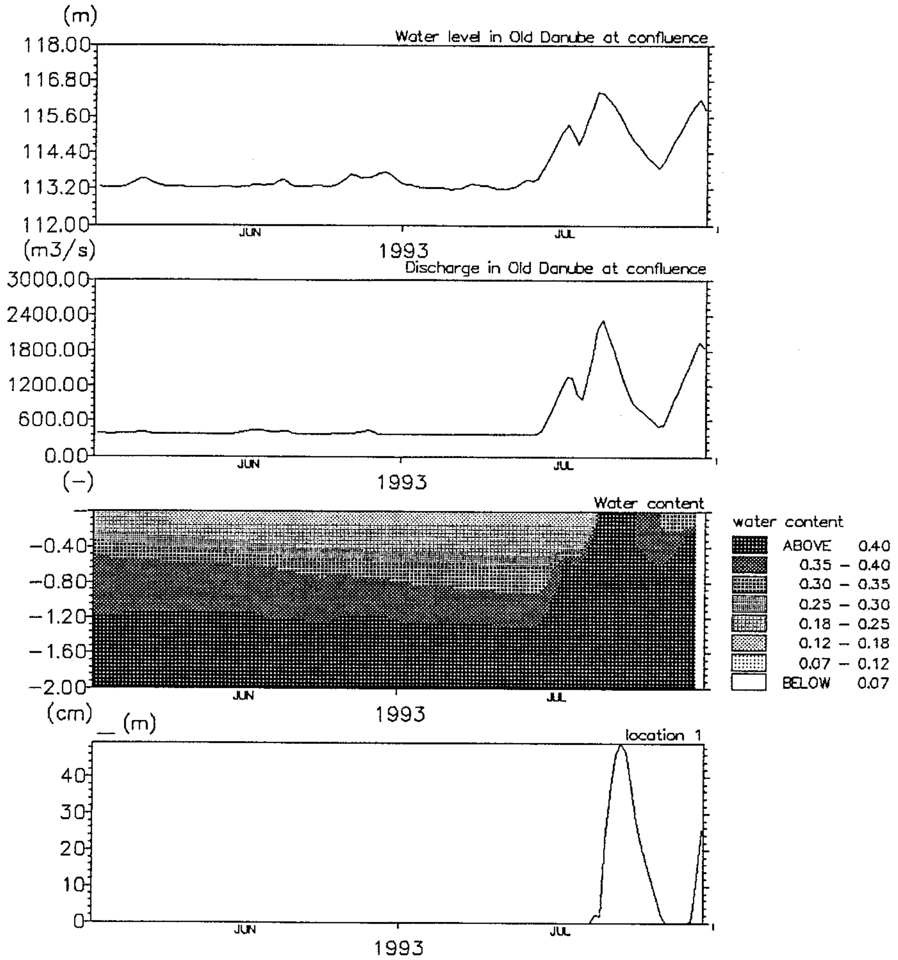


Figure 12. Simulated discharge and water levels in the Danube at the confluence between Danube and the outlet canal from the hydropower plant; simulated moisture contents at the upper two meter of the soil profile at location 1 and simulated depths of inundation at location 1 in the river branch system during June–July 1993.

have been determined from ecological considerations according to requirements of (semi)terrestrial (floodplain) ecotopes. From the figure the contacts between the main Danube river and the river branch system is clearly seen. Similar computations have been made by alternative water management schemes after damming of the Danube. The results of one of the hypothetical post-dam water management regimes, characterized by average water flows in the power canal, Danube and river branch system intake of 1470 $m^3\ s^{-1}$, 400 $m^3\ s^{-1}$ and 45 $m^3\ s^{-1}$, respectively, are shown in Figure 14. By comparing Figure 13 and Figure 14 the differences in hydrological conditions can clearly be seen. For instance the pre-dam conditions (Figure 13) are in many places characterised by high groundwater tables

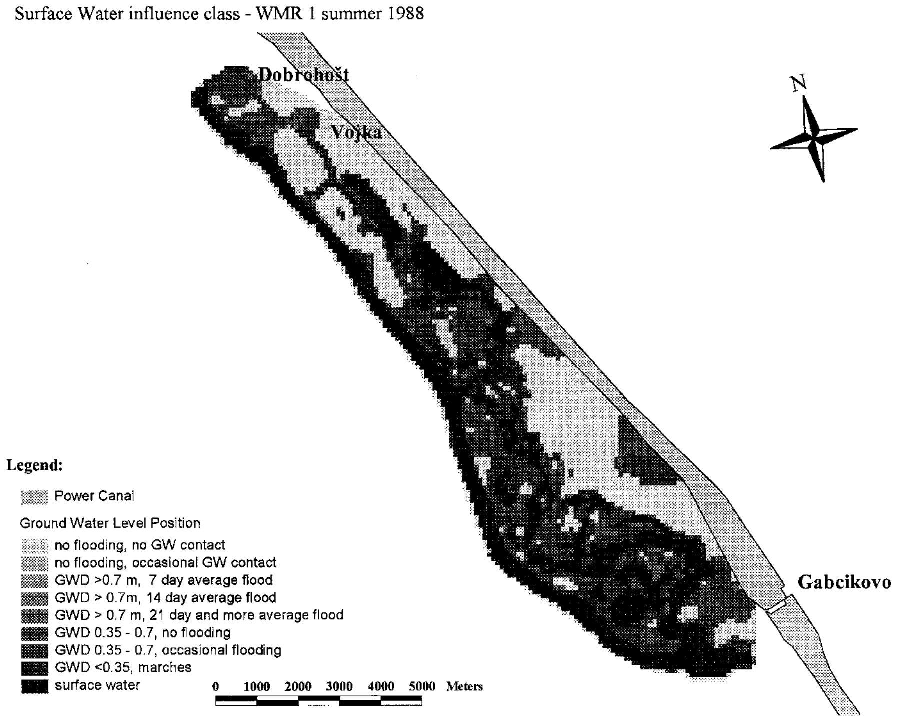


Figure 13. Hydrological regime in the river branch area for 1988 pre-dam conditions characterized in ecological classes.

and small/seldom flooding, while the post-dam situation (Figure 14) generally has deeper ground water tables and more frequent flooding. From such changes in hydrological conditions inferences can be made on possible changes in the floodplain ecosystem.

Further scenarios (not shown here) have, amongst others, investigated the effects of establishing underwater weirs in the Danube and in this way improvement of the connectivity between the Danube and the river branch system.

7. Limitations in the Couplings made in the Integrated Model

The integrated modelling system and the way it was applied includes different degrees of integration ranging from sequential runs, where results from one model are used as input to the next model, to a full integration, such as the coupling between MIKE SHE and MIKE 11. Hence, the system is not truly integrated in all respects. The justification for these different levels lies in assessments of where it was required in the present project area to account for feed back mechanisms and where such feed backs could be considered to be of minor importance for all practical purposes. For other areas with different hydrological characteristics, the required levels of integration are not necessarily the same. Therefore, a discussion

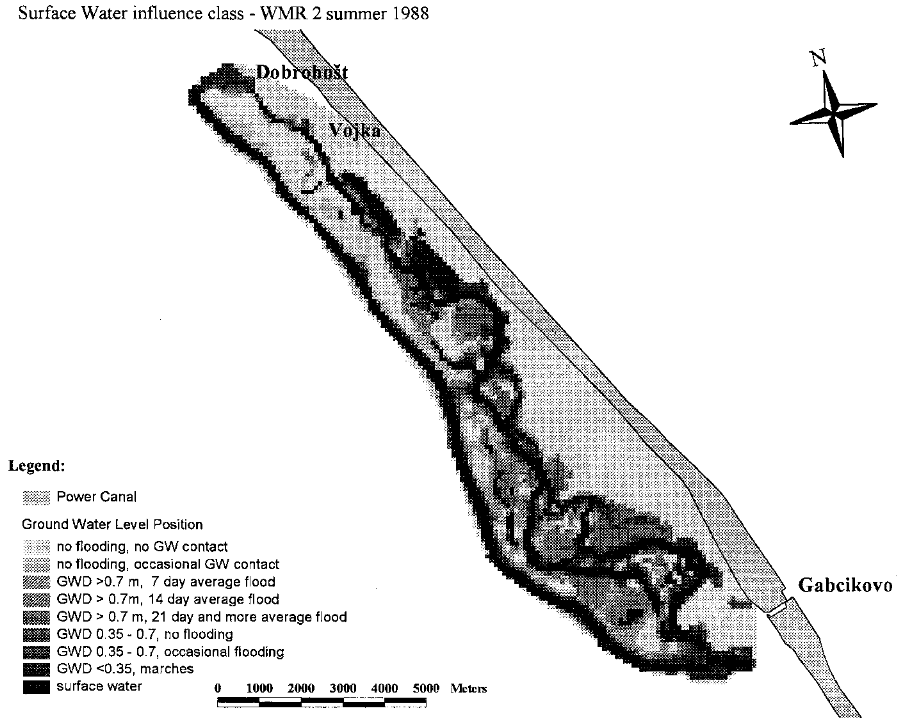


Figure 14. Hydrological regime in the river branch area for a post-dam water management regime characterized in ecological classes. The scenario has been simulated using 1988 observed upstream discharge data and a given hypothetical operation of the hydraulic structures.

is given below on the universality and limitations of the various couplings made in the present case.

A. Hydrological catchment/river hydraulics (MIKE SHE/MIKE 11)

This coupling between the hydrological code and the river hydraulic code is fully dynamic and fully integrated with feed back mechanisms between the two codes within the same computational time step. This coupling cannot be treated sequentially in this area, since the feedback between river and aquifer works in both directions, with the river functioning as a source in part of the area and as a drain in other parts, and since the direction of the stream-aquifer interaction changes dynamically in time and space as a consequence of discharge fluctuations in the Danube. This coupling was shown to be crucial during the course of the project, and, due to the full integration, it is fully generic.

B. Reservoir/river (MIKE 21/MIKE 11)

This coupling is a simple one-way coupling with the reservoir model providing input data to the downstream river model, both in terms of sediment and water quality parameters. This coupling is sufficient in the present case, because there is no feedback from the downstream river to the reservoir. Even though this coupling is not fully generic, it may be sufficient in most cases, even in cases with a network of reservoirs and connecting river reaches.

C. Reservoir/groundwater water exchange (MIKE 21/MIKE SHE)
This coupling is a simple one-way coupling with the reservoir model providing data on sedimentation to the groundwater module of MIKE SHE, where they are used to calculate leakage coefficients in the surface water/ground water flow calculations. This coupling is sufficient in the present case, where the reservoir water table always is higher than the ground water table, and where the flow always is from the reservoir to the aquifer. However, for cases where water flows in both directions, or where there are significant temporal variations in the sedimentation, the present coupling is not necessarily sufficient.

D. Hydrology catchment/crop growth (MIKE SHE/DAISY)
This coupling is an iterative coupling with data flowing in both directions. However, it is not a full integration with the two model codes running simultaneously. Therefore, a number of iterations are required until the input data used in MIKE SHE (vegetation data simulated by DAISY) generates the input data used in DAISY (ground water levels) and vice versa. For example, changes in river water levels affect the ground water levels, implying that the crop growth conditions change and hence, the DAISY simulated vegetation data used by MIKE SHE to simulate the ground water levels are not correct. In such a case, the MIKE SHE simulation has to be repeated with the new crop growth data and subsequently, the DAISY simulation has to be repeated with the new ground water levels, etc., until the differences become negligible. This coupling has been used successfully in previous studies (Styczen and Storm, 1993), but may, due to the iterative mode, be troublesome in practise.

E. Surface water/ground water quality (MIKE 11 – MIKE 21/MIKE SHE)
In contrary to the full coupling of flows (coupling A) the corresponding water quality coupling is a simple one-way coupling with the river and reservoir models providing the water quality parameters in the infiltrating water and uses these as boundary conditions for the ground water quality simulations. This coupling is sufficient in the present case with respect to the reservoir, where the flow always is from the reservoir to the aquifer. The river-aquifer interaction involves flows in both directions, but the return flow from the aquifer to the Danube is very small (about 1%) as compared to the Danube flow, and hence, the feedback from the ground water quality to Danube water quality is assumed negligible. However, for other cases where the mass flux from the aquifer to the river system is important for the river water quality, the present one-way coupling will not be sufficient.

8. Discussion and Conclusions

The hydrological and ecological system of the Danubian Lowland is so complex with so many interactions between the surface and the subsurface water regimes and between physical, chemical and biological changes, that an integrated numerical modelling system of the distributed physically-based type is required in order to provide quantitative assessments of environmental impacts on the ground water, the surface water and the floodplain ecosystem of alternative management options for the Gabcikovo hydropower scheme.

Such an integrated modelling system has been developed, and an integrated model has been constructed, calibrated and, to the extent possible, validated for the 3000 km^2 area. The individual components of the modelling system represent state-of-the-art techniques within their respective disciplines. The uniqueness is the full integration. The integrated system enables a quite detailed level of modelling, including quantitative predictions of the surface and ground water regimes in the floodplain area, ground water levels and dynamics, ground water quality, crop yield and nitrogen leaching from agricultural land, sedimentation and erosion in rivers and reservoirs, surface water quality as well as frequency, magnitude and duration of inundations in floodplain areas. The computations were carried out on Hewlett Packard Apollo 9000/735 UNIX workstations with 132 MB RAM. With a 300 MHz Pentium II NT computer a typical computational times for one of the steps described in Section 6.2 (Figure 10) would be 2–10 hr. Thus, although the integrated system is rather computationally demanding, the computational requirements are not a serious constraint in practise as compared to the demand for comprehensive field data.

For most of the individual model components, traditional split-sample validation tests have been carried out, thus documenting the predictive capabilities of these models. However, this was not possible for some aspects of the integrated model. Hence, according to rigorous scientific modelling protocols, the integrated model can be argued to have a rather limited predictive capability associated with large uncertainties. A theoretical analysis of error propagation in such an integrated model would be quite interesting, but was outside the scope of the present study which was limited to the comprehensive task of developing the integrated modelling system and establishing the integrated model on the basis of all available data. However, on the basis of the few possible tests (e.g. Figure 7) of the integrated model against independent data not used in the calibration-validation process for the individual models, it is our opinion that the uncertainties of the integrated model are significantly smaller than those of the individual models. The two key reasons for this are: (1) in the integrated model the internal boundaries are simulated by neighbouring model components and not just assessed through qualified but subjective estimates by the modeller; and (2) the integrated model makes it possible to explicitly include more sources of data in validation tests that can not all be utilised in the individual models. Thus, by adding independent validation tests for the integrated model, such as the one shown in Figure 7 on discharges in seepage canals, to the validation tests for the individual models, the outputs of the integrated model have been subject to a more comprehensive test based on more data and hence, must be considered less uncertain than outputs from the individual models.

The environmental impacts of the new reservoir and the diversion of water from the Danube through the Gabcikovo power plant can be simulated in rather fine detail by the integrated model established for the area. The integrated nature of the model has been illustrated by a case study focusing on hydrology and ecology in the wetland comprising the river branch system. The integrated model is not claimed to be capable of predicting detailed ecological changes at the species level. However, it is believed to be capable of simulating changes in the hydrological regime resulting from alternative water management decisions to such a degree of detail that it becomes a valuable tool for broader assessments of possible ecological changes in the area.

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References

Bathurst, J. C., Wicks, J. M. and O’Connel, P. E.: 1995, The SHE/SHESED basin scale water flow and sediment transport modelling system, In V. P. Singh (ed.), *Computer Models of Watershed Hydrology*, Water Resources Publications, pp. 563–594.

Calver, A. and Wood, W. L.: 1995, The institute of hydrology distributed model, In V. P. Singh (ed.), *Computer Models of Watershed Hydrology*, Water Resources Publications, pp. 595–626.

CEC: 1991, Commission of European Communities, Czech and Slovak Federative Republic, Danubian Lowland-Ground Water Model, No. PHARE/90/062/030/001/EC/WAT/1

DHI: 1995, MIKE 21 Short Description. Danish Hydraulic Institute, Hørsholm, Denmark.

DHI, DHV, TNO, VKI, Krüger and KVL: 1995, PHARE project Danubian Lowland – Ground Water Model (EC/WAT/1), Final Report. Prepared by a consultant group for the Ministry of the Environment, Slovak Republic and for the Commission of the European Communities, Vol. 1, 65 pp.; Vol. 2, 439 pp.; Vol. 3, 297 pp., Bratislava.

EC: 1992, Working group of independent experts on variant C of the Gabcikovo-Nagymaros project, working Group Report, Commission of the European Communities, Czech and Slovak Federative Republic, Republic of Hungary, Budapest, 23 November, 1992.

EC: 1993a, Working group of monitoring and water management experts for the Gabcikovo system of locks – Data Report, Commission of the European Communities, Republic of Hungary, Slovak Republic, Budapest, 2 November, 1993.

EC: 1993b, Working group of monitoring and water management experts for the Gabcikovo system of locks – Report on temporary water management regime, Commission of the European Communities, Republic of Hungary, Slovak Republic, Bratislava, 1 December, 1993.

Engesgaard, P.: 1996, Multi-Species Reactive Transport, In M. B. Abbott and J. C. Refsgaard (eds), *Distributed Hydrological Modelling*, Kluwer Academic Publishers, pp. 71–91.

Griffioen, J., Engesgaard, P., Brun, A., Rodak, R., Mucha, I. and Refsgaard, J. C.: 1995, Nitrate and Mn-chemistry in the alluvial Danubian Lowland aquifer, Slovakia. *Ground Water Quality: Remediation and Protection (GQ95)*, Proceedings of the Prague Conference, May 1995, IAHS Publ. No. 225, pp. 87–96.

Hansen, S., Jensen, H. E., Nielsen, N. E. and Svendsen, H.: 1991, Simulation of nitrogen dynamics and biomass production in winter wheat using the Danish simulation model DAISY. *Fertilizer Research* **27**, 245–259.

Havnø, K., Madsen, M. N. and Dørge, J.: 1995, 'MIKE 11 – A Generalized River Modelling Package', In V. P. Singh (ed), *Computer Models of Watershed Hydrology*, Water Resources Publications, pp. 733–782.

Holobrada, M., Capekova, Z., Lukac, M. and Misik, M.: 1994, Prognoses of the Hrusov reservoir eutrophication and siltation under various discharge distribution to the Old Danube (in Slovak), Water Research Institute (VUVH), Bratislava.

ICJ: 1997, Case Concerning Gabcikovo-Nagymaros project (Hungary/Slovakia). Summary of the Judgement of 25 September 1997. International Court of Justice, The Hague, (available on www.icj-cij.org).

JAR: 1995, 1996, 1997, Joint Annual Report of the environment monitoring in 1995, 1996, 1996 according to the 'Agreement between the Government of the Slovak Republic and the Government of Hungary about Certain Temporary Measures and Discharges to the Danube and Mosoni Danube', signed 19 April, 1995.

Klemes, V.: 1986, Operational testing of hydrological simulation models, *Hydrological Sciences Journal*, 13–24.

Klucovska, J. and Topolska, J.: 1995, Water regime in the Danube river and its river branches, In I. Mucha (ed.), *Gabcikovo Part of the Hydroelectric Power Project. Environmental Impact Review*, Faculty of Natural Sciences, Comenius University, Bratislava, pp. 33–42.

Kocinger, D.: 1995, Gabcikovo Part of the Hydroelectric Power Project, Basic Characteristics, In I. Mucha (ed.), *Gabcikovo Part of the Hydroelectric Power Project – Environmental Impact Review,* Faculty of Natural Sciences, Comenius University, Bratislava, pp. 5–14.

Koncsos, L., Schütz, E. and Windau, U.: 1995, Application of a comprehensive decision support system for the water quality management of the river Ruhr, Germany, In S. P. Simonovic, Z. Kunzewicz, D. Rosbjerg and K. Takeuchi (eds), *Modelling and Management of Sustainable Basin-Scale Water Resources Systems*, IAHS Publ. No. 231, pp. 49–59.

Menetti, M.: 1995, Analysis of regional water resources and their management by means of numerical simulation models and satellites in Mendoza, Argentina, In S. P. Simonovic, Z. Kunzewicz, D. Rosbjerg and K. Takeuchi (eds), *Modelling and Management of Sustainable Basin-Scale Water Resources Systems*, IAHS Publ. No. 231, pp. 49–59.

Mucha, I.: 1992, Database processing of the hydropedological parameters for the ground water flow model of the Danubian Lowland (in Slovak), Ground Water Division, Faculty of Natural Science, Comenius University, Bratislava.

Mucha, I., Paulikova, E., Hlavaty, Z., Rodak, D. and Pokorna, L.: 1992a, Danubian Lowland Ground Water Model, Working Manual to consortium of invited specialists for workshop in Bratislava, Ground Water Division, Faculty of Natural Sciences, Comenius University, Bratislava.

Mucha, I., Paulikova, E., Hlavaty, Z. and Rodak, D.: 1992b, Elaboration of basis data for preparation of hydrogeological parameters for the model of the ground water flow of the Danubian Lowland area (in Slovak), Ground Water Division, Faculty of Natural Science, Comenius University, Bratislava.

Mucha, I., Paulikova, E., Hlavaty, Z., Rodak, D. and Pokorna, L.: 1993, Surface and ground water regime in the Slovak part of the Danube alluvium, Ground Water Division, Faculty of Natural Science, Comenius University.

Mucha, I. (ed): 1995, Gabcikovo part of the hydroelectric power project environmental impact review. Evaluation based on two years monitoring, Faculty of Natural Sciences, Comenius University, Bratislava.

Mucha, I., Rodak, D., Hlavaty, Z. and Bansky, L.: 1997, Environmental aspects of the design and construction of the Gabcikovo Hydroelectric Power Project on the river Danube, *Proceedings International Symposium on Engineering Geology and the Environment*, organized by the Greek National Group of IAEG, Athens, June 1997, Engineering Geology and the Environment, pp. 2809–2817.

Nachtnebel, H.-P. (ed): 1989, Ökosystemstudie Donaustau Altenwörth, Veränderungen durch das Donaukraftwerk Altenwörth, Österreische Akademie der Wissenschaften, Veröffentlichungen des Österreischen MaB-Programs, Band 14, Universitätsverlag Wagner, Innsbruck.

Person, M., Raffensperger, J. P., Ge, S. and Garven, G.: 1996, Basin-scale hydrogeologic modelling, *Rev. Geophys.* **34**(1), 61–87.

Perspektiven: 1989, Staustufe Freudenau, *Perspektiven, Magazin für Stadtgestaltung und Lebensqualität*, Dezember 1989.

Refsgaard, J. C.: 1997, Parameterisation, calibration and validation of distributed hydrological models, *J. Hydrology* **198**, 69–97.

Refsgaard, J. C. and Storm, B.: 1995, MIKE SHE, In V. P. Singh (ed), *Computer Models of Watershed Hydrology*, Water Resources Publications, pp. 809–846.

Singh, V. P. (ed): 1995, *Computer Models of Watershed Hydrology*, Water Resources Publications.

Sørensen, H. R., Klucovska, J., Topolska, T., Clausen, T. and Refsgaard, J. C.: 1996, An engineering case study – Modelling the influences of the Gabcikovo hydropower plant in the hydrology and ecology in the Slovak part of the river branch system, In M. B. Abbott and J. C. Refsgaard (eds), *Distributed Hydrological Modelling*, Kluwer Academic Publishers, pp. 233–253.

Styczen, M. and Storm, B.: 1993, Modelling of N-movements on catchment scale – a tool for analysis and decision making. 1. Model description. 2. A case study, *Fertilizer Research* **36**, 1–17.

Topolska, J. and Klucovska, J.: 1995, River morphology, In I. Mucha (ed.), *Gabcikovo Part of the Hydroelectric Power Project. Environmental Impact Review*, Faculty of Natural Sciences, Comenius University, Bratislava, pp. 23–32.

VKI: 1995, Short Description of water quality and eutrophication modules,. Water Quality Institute, Hørsholm, Denmark.

Winter, T. C.: 1995, Recent advances in understanding the interaction of groundwater and surface water, *Rev. Geophys.*, Supplement, U.S. National Report 1991–94 to IUGG, pp. 985–994.

Yan, J. and Smith, K. R.: 1994, Simulation of integrated surface water and ground water systems – model formulation, *Water Resources Bulletin* **30**(5), 879–890.